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Optimum combined pitch and trailing edge flap control

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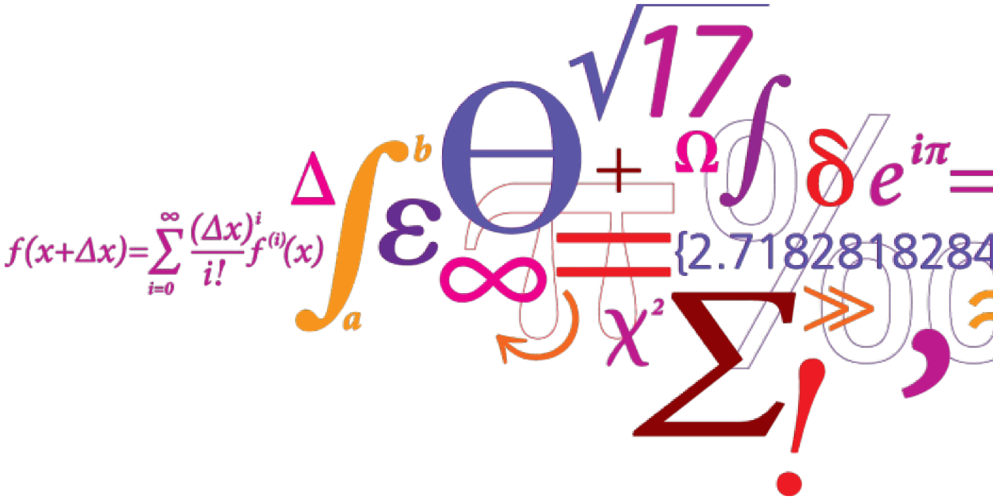


Session 5.3 Aerodynamics

Danish Wind Power Research 2013

Trinity Gl. Færgevej 30, Fredericia

May 27-28, 2013

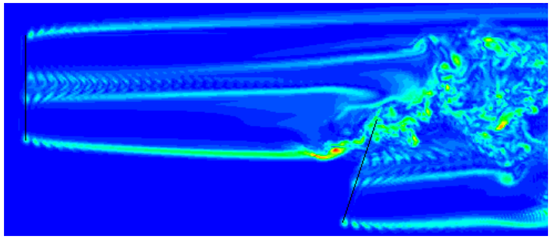
DTU Wind Energy
Department of Wind Energy

Structure of the presentation

- Introduction
  - Why Smart Rotors? Why a combined control framework?
- Model Based Control Framework
  - Problem formulation
  - Aerodynamic and structural models
  - Verification: compare response on the structure
- Simulation Test Case
- Applications and results
  - Focus on Blade Root Loads Alleviation
- Other applications (preliminary):
  - Increase power capture?
- Conclusion and Future Work

Introduction

Why Smart Rotors?



- Wind turbine operate in non uniform wind field
- What is a smart rotor?
  - Combination of sensors, control unit, actuators
  - Actively reduces the loads it has to withstand
  - Actuators:
    - Blade Pitch
    - Distributed aerodynamic control (Trailing Edge Flaps)

- Literature: simulation and a few experiments
  - Different configurations & conditions
  - Widespread figures (from 5 % to 45 %)
  - All confirm load alleviation

- Active load alleviation
  - Road to up-scaling?
  - Road to decreased Cost of Energy?
  - Next level challenge/solution?

Introduction

Why a combined control framework?

- Traditional smart rotor control approach:
  - 'classic' power regulation control unmodified
  - Superimposed control for load alleviation
  - Avoid interferences by frequency separation

Aim of the investigation:

Outline a combined control framework, explore its possibility, and its advantages

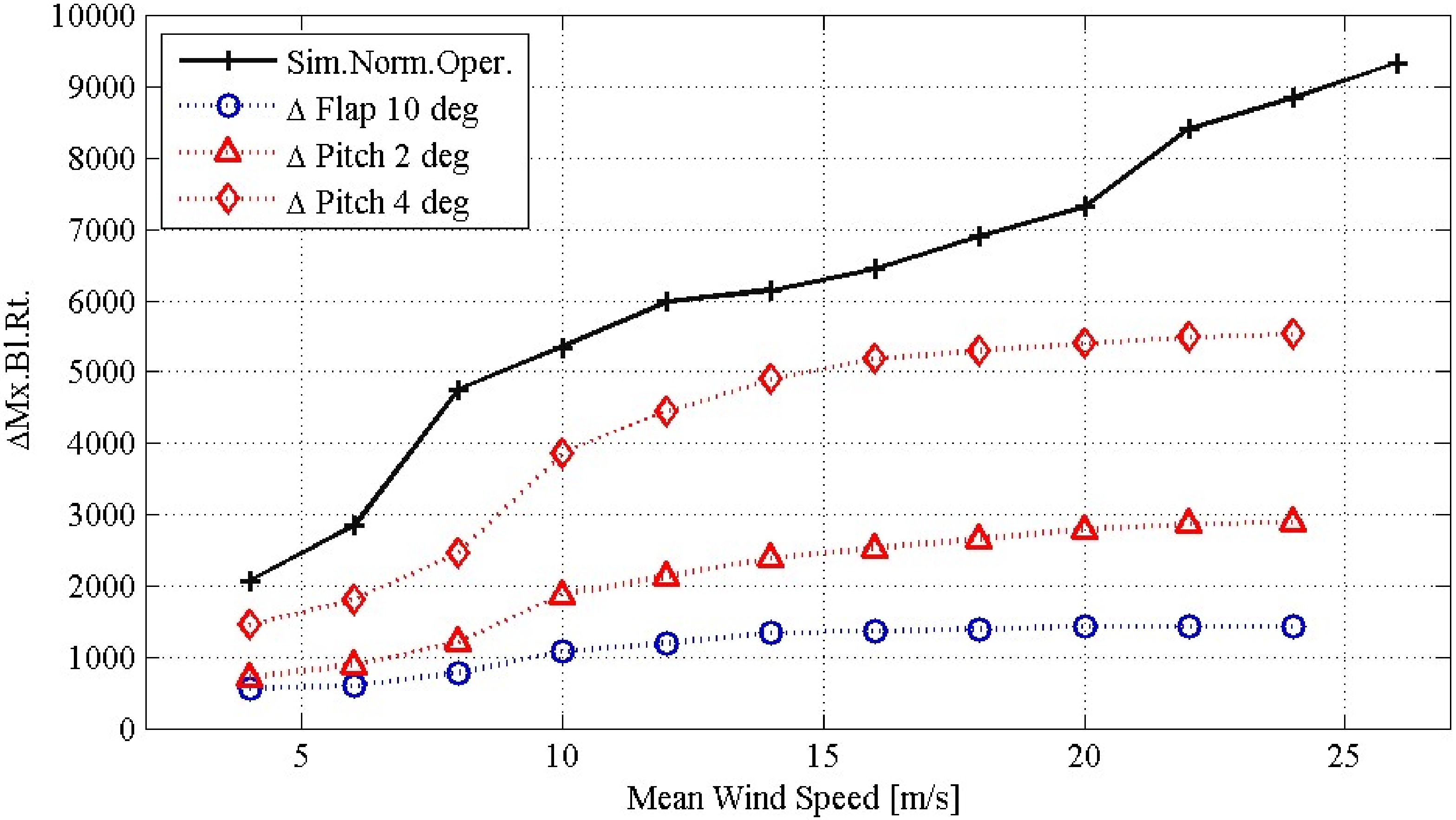
- A single control system integrates generator, pitch, and distributed device control

- <u>Main focus</u>: Application to blade load alleviation
- Other application are possible:
  - Enhanced energy capture below rated conditions (preliminary)
  - Drive train and generator load alleviation
  - ...

Introduction

Why a combined control framework?

- "In union there is strength"…
- Load variation in IEC conditions compared to actuator variation



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How: Model Based Control framework

- Formulated as Model Predictive Control problem:
  - ***Optimal control***:

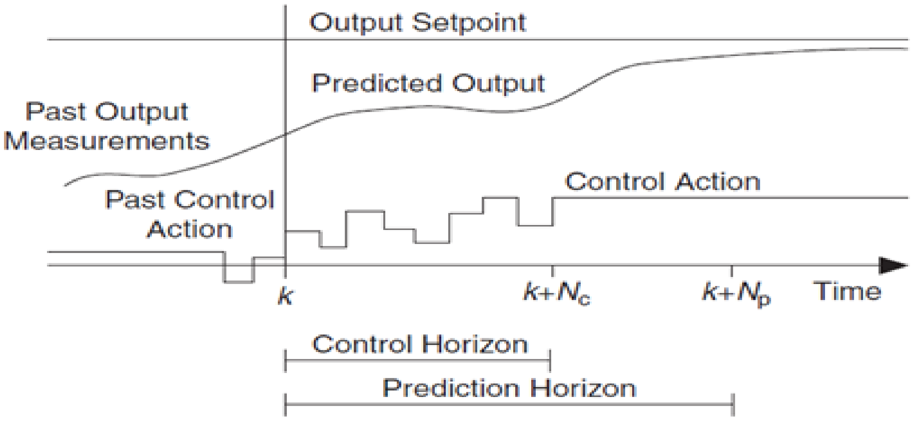
    Minimizes objective function: $$J = f\left(\bar{x}, \bar{u}, \bar{w}\right)$$

    s.t. a set of constraints

  - ***Model Based control:***

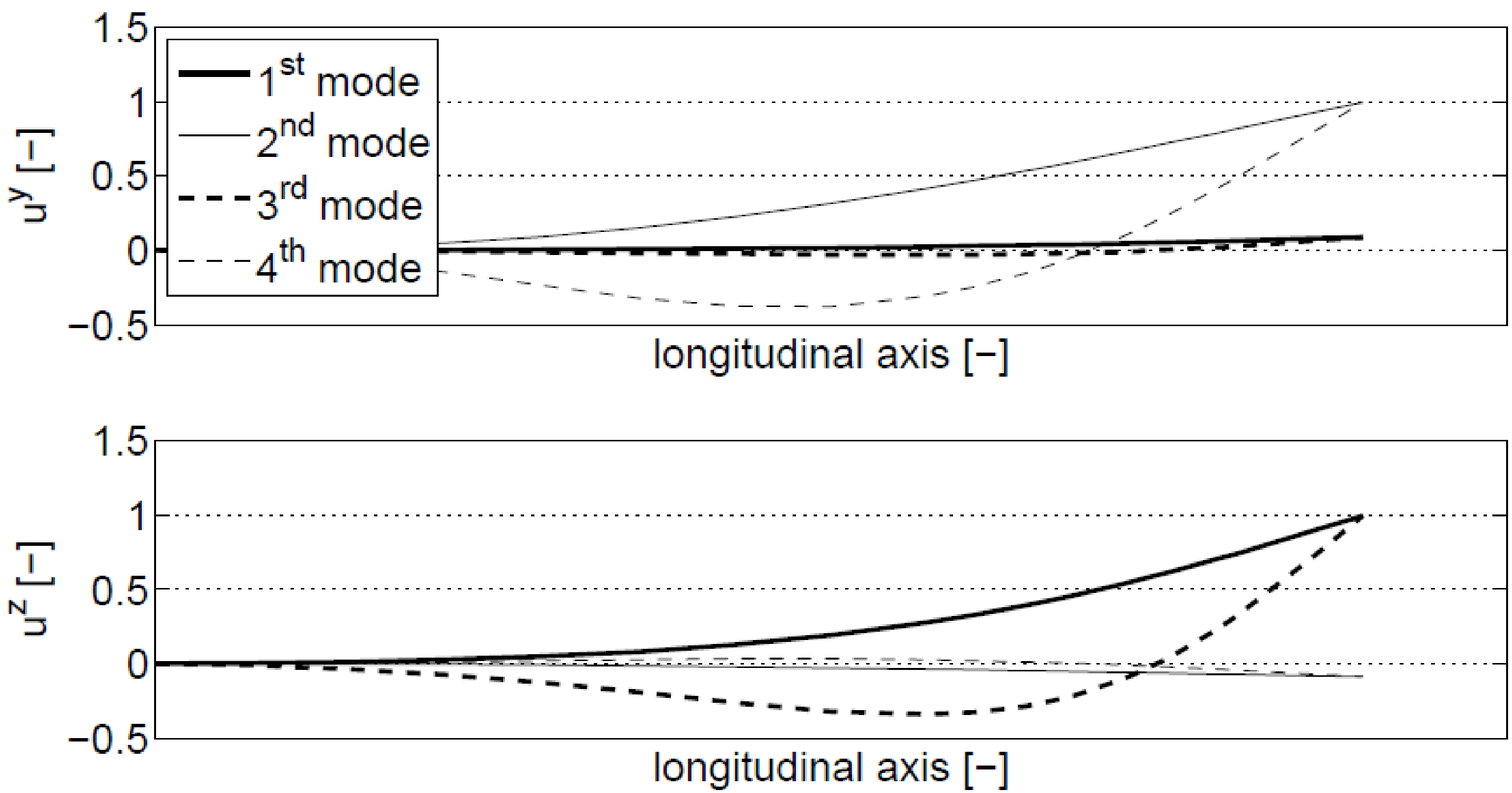
    Control design requires a model of the system to control

    - Linear model
    - Capture relevant dynamics ⇔ simple model
    - Aeroelastic problem: model structure & aerodynamics
    - (First principle model)



Structural model (in MPC)

- Modal shape function approach (simplified model):
  - Superposition of deflection shape functions → Component deflection
  - Deflection shape → Eigenmodes
  - Tower 1 FA + 1SS, Drive Train 1 Torsion
  - Blade: 2 Mx + 2 My



Model Based control framework

Aerodynamic model (in MPC)

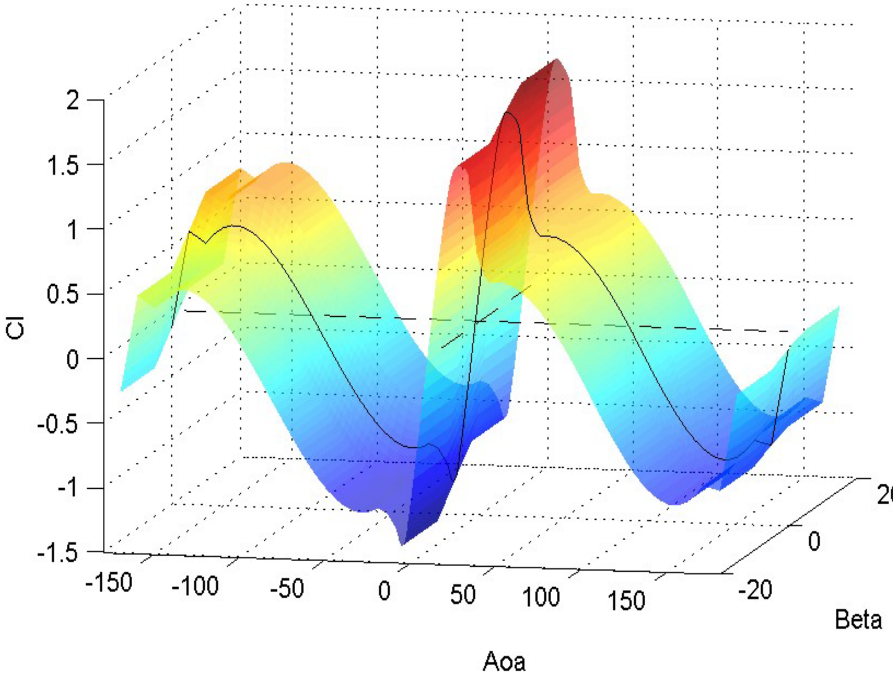
- Linearized BEM-based formulation:
  - Compute a-priori (quasi-steady lookup):
    - Integral aerodynamic forces $C_l(\alpha,\beta)$
    - Induction velocities $a(\theta,\lambda,\beta)$
    - Linearized dependence on flap
  - Dynamic inflow as 1st order filter

Lift and drag

- $L = \frac{1}{2}\rho W^2 C_L(\alpha,\beta) \approx \frac{1}{2}\rho W^2 C_L(\alpha,0) + \frac{1}{2}\rho W^2 \frac{\partial C_L(\alpha,0)}{\partial\beta}\beta$
- $D = \frac{1}{2}\rho W^2 C_D(\alpha,\beta) \approx \frac{1}{2}\rho W^2 C_D(\alpha,0) + \frac{1}{2}\rho W^2 \frac{\partial C_D(\alpha,0)}{\partial\beta}\beta$

Induction factors normal and tangential to the rotor plane

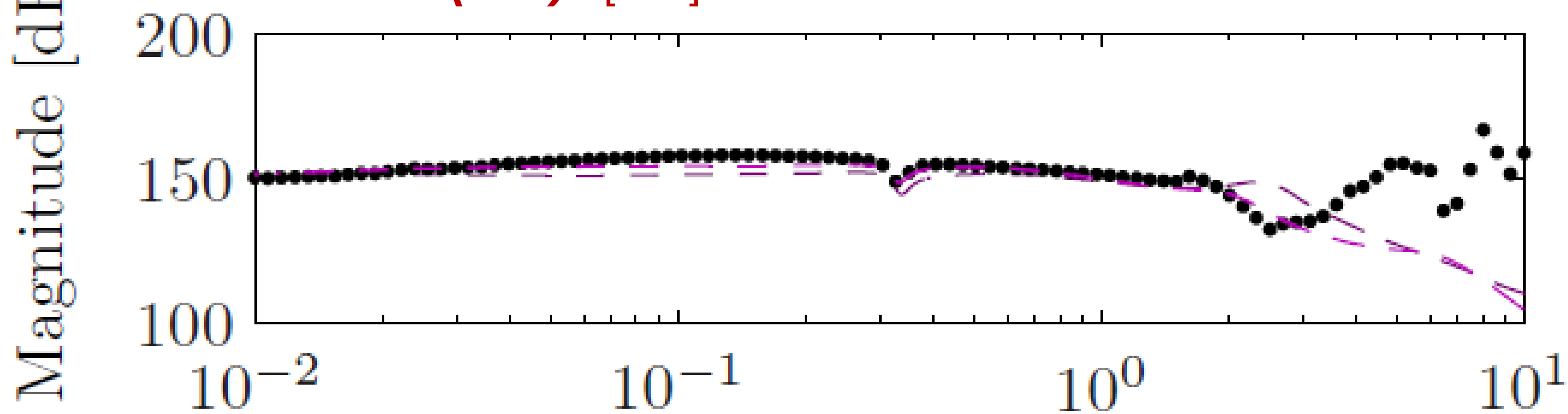
- $a(\theta,\lambda,\beta) \approx a(\theta,\lambda,0) + \frac{\partial a(\theta,\lambda,0)}{\partial\beta}\beta$
- $a'(\theta,\lambda,\beta) \approx a'(\theta,\lambda,0) + \frac{\partial a'(\theta,\lambda,0)}{\partial\beta}\beta$



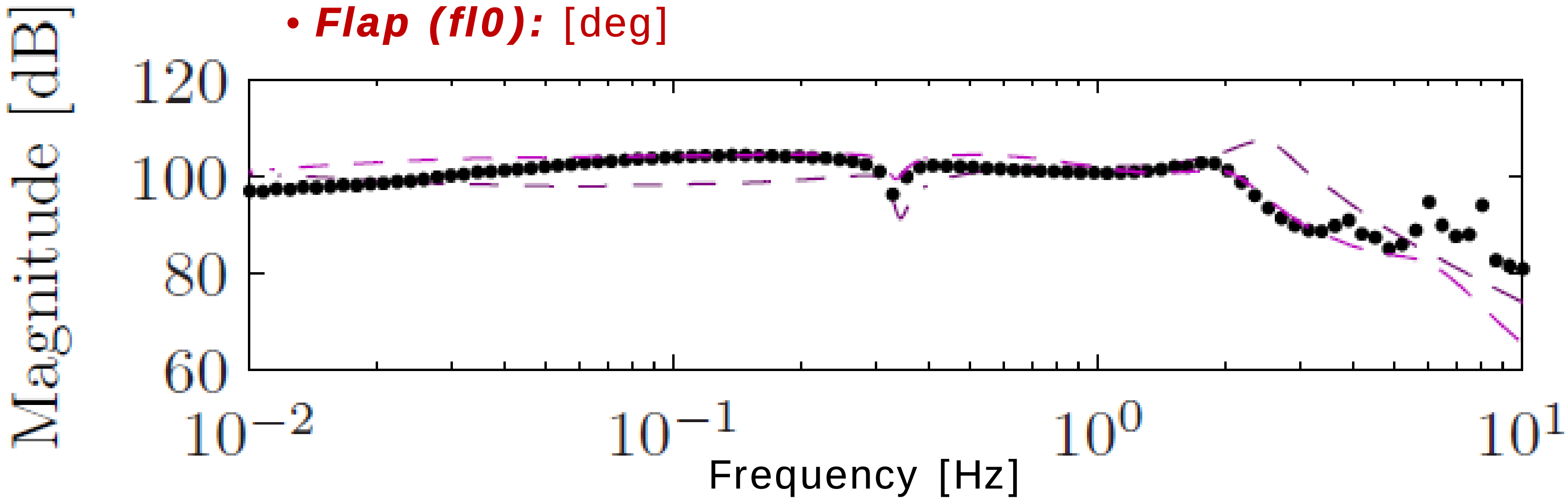
Verification: Response on blade root

Purple: 2+2 blade modes
Blue: 3+3 blade modes

- ***Pitch (th0):*** [rad]



- ***Flap (fl0):*** [deg]



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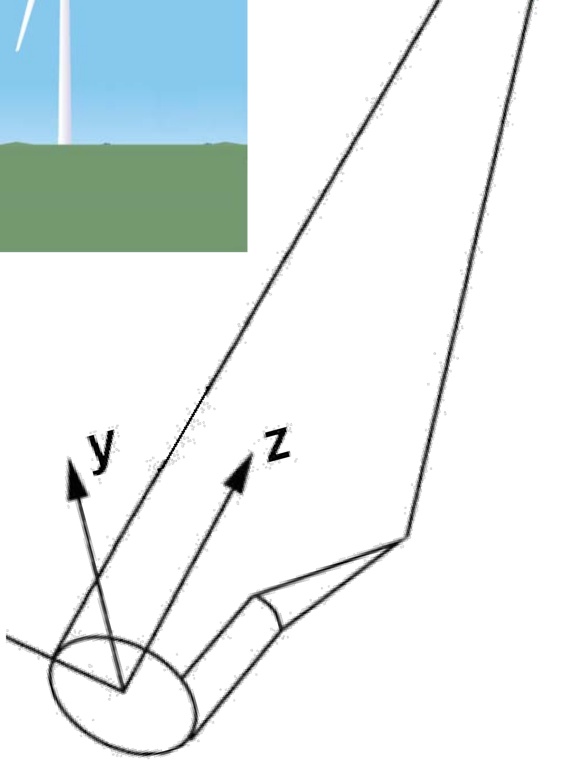
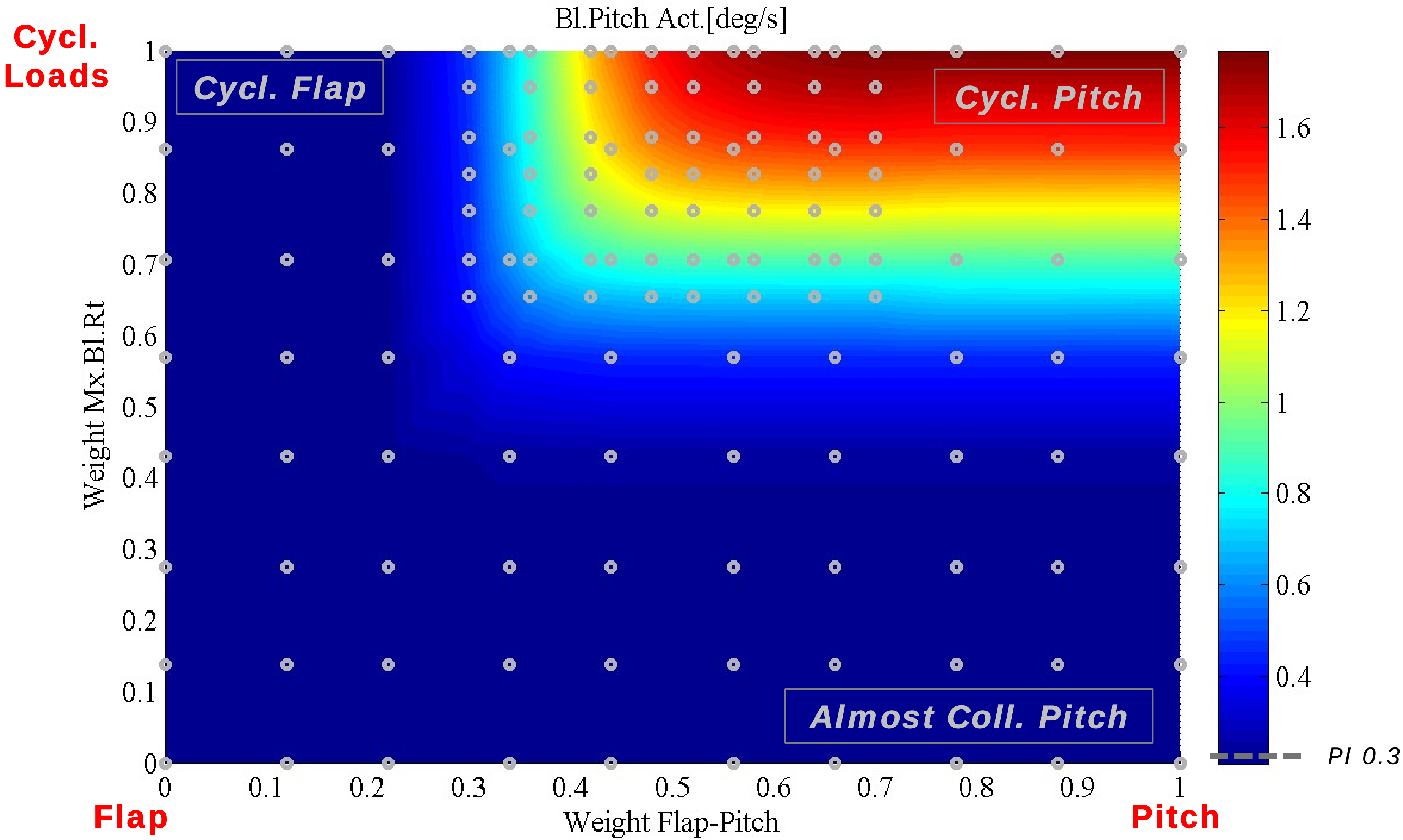
Simulation Test Case

- Reference NREL 5 MW turbine
- Adaptive Trailing Edge Flaps
  - All flaps on one blade moved as one
- Sensors:
  - Shaft sp., Blade root b.mom, Tower top acc.
- Simulations with HAWC2
  - Multibody dynamics, includes torsion
  - Unsteady BEM aerodynamics
- IEC conditions: class A. Iref:0.16 (wsp: 18 m/s)
- Focus on blade load alleviation



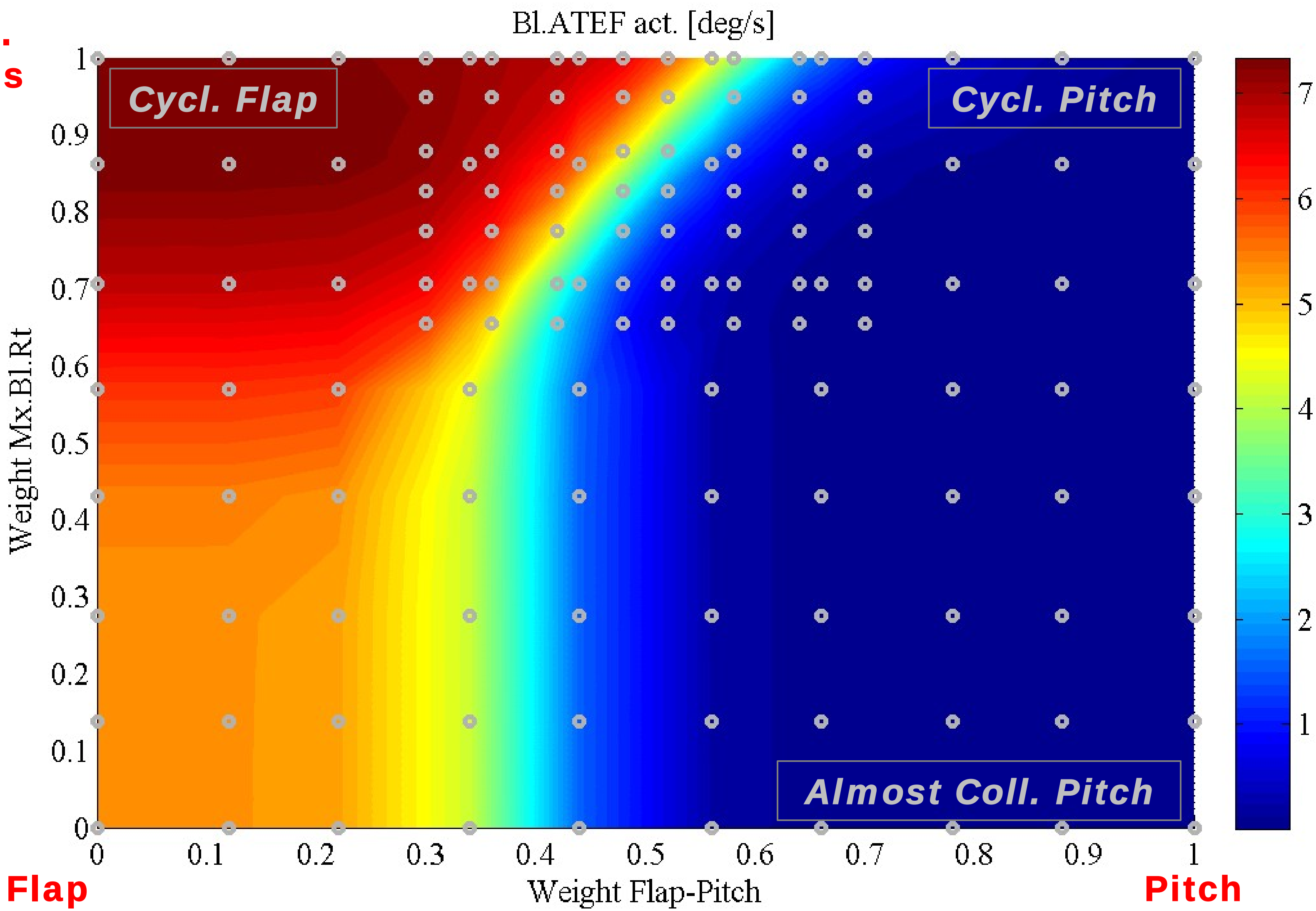
Reference Wind Turbine		*Flap Setup*	
Rat. Power	5 MW	Chordwise ext.	10%
Num.Blades	3	Deflect.limits	$\pm 10^\circ$
Rotor Diam.	126 m	Max. ΔCl	$-0.45 \sim +0.41$
Blade length	61.5 m	Spanwise length	12.3 m (20% blade length)
Rat. Rot.Sp.	1.267 rad/s	Spanwise loc.	from 47.7 m to 60.0 m span
Hub height	90 m	Max.ΔMx.Bl.Rt	approx. $\pm$1100 kNm

Blade Root Loads Alleviation



Blade Root Loads Alleviation

Cycl. Loads

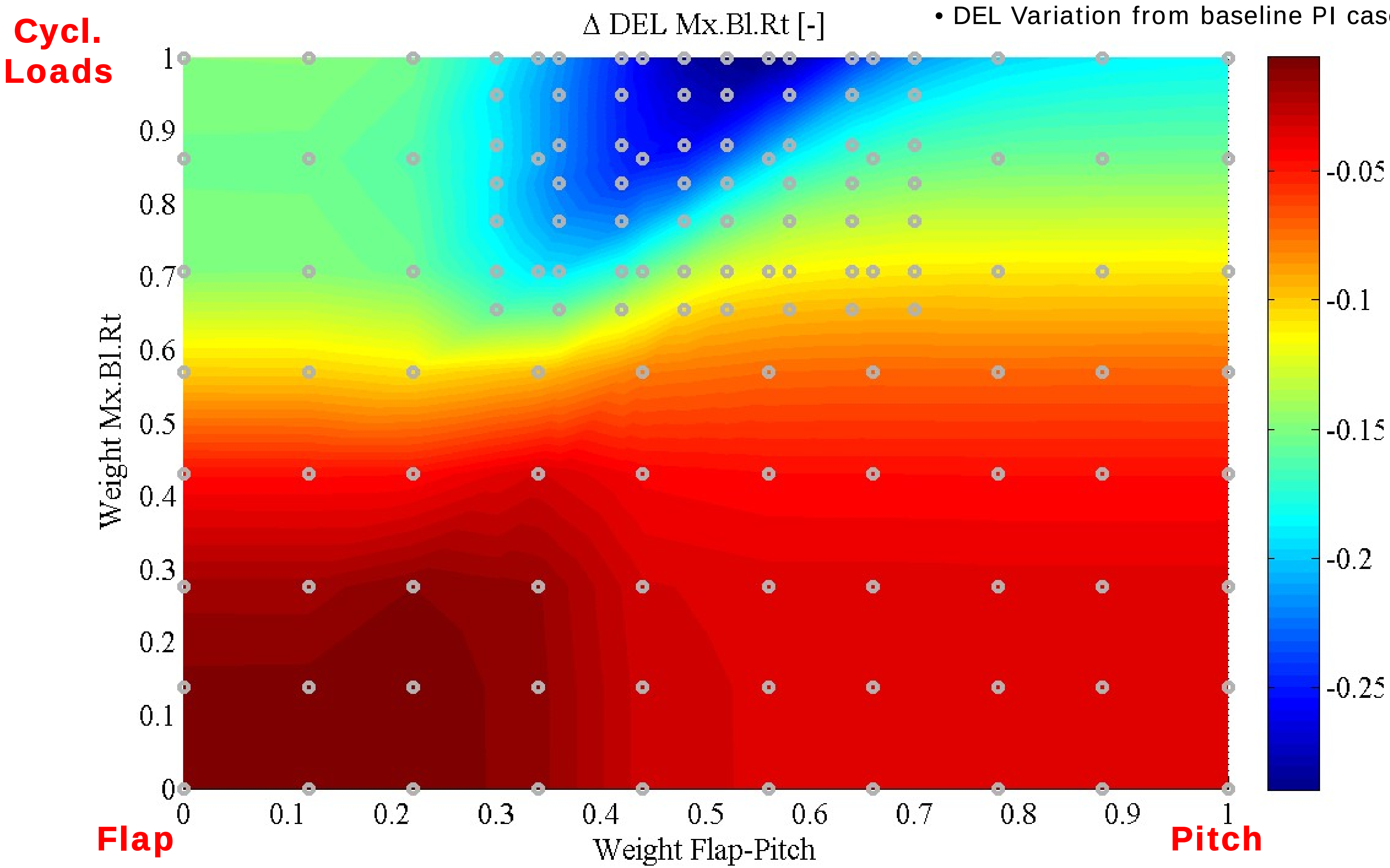


Flap

Pitch

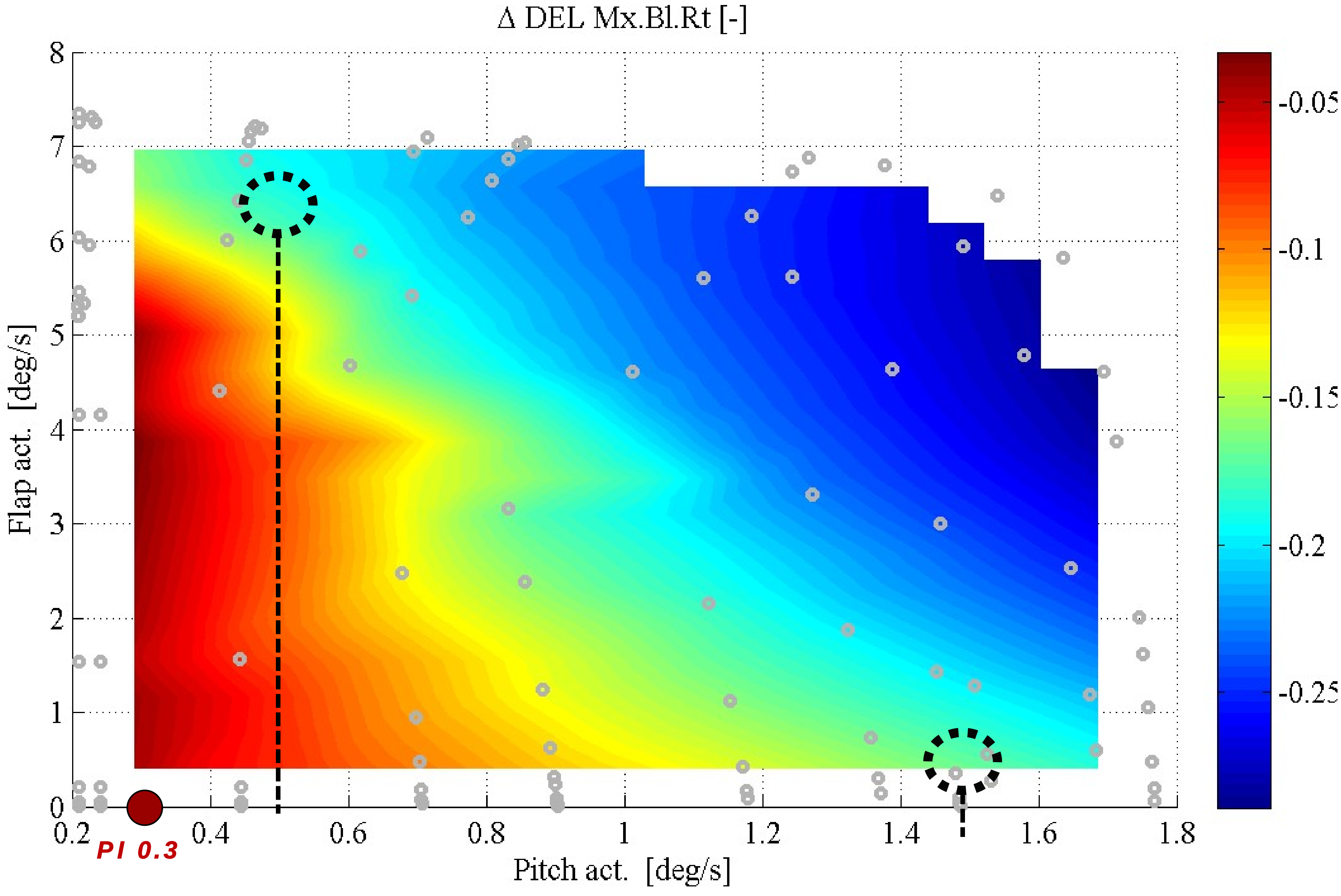
Blade Root Loads Alleviation

- DEL Variation from baseline PI case



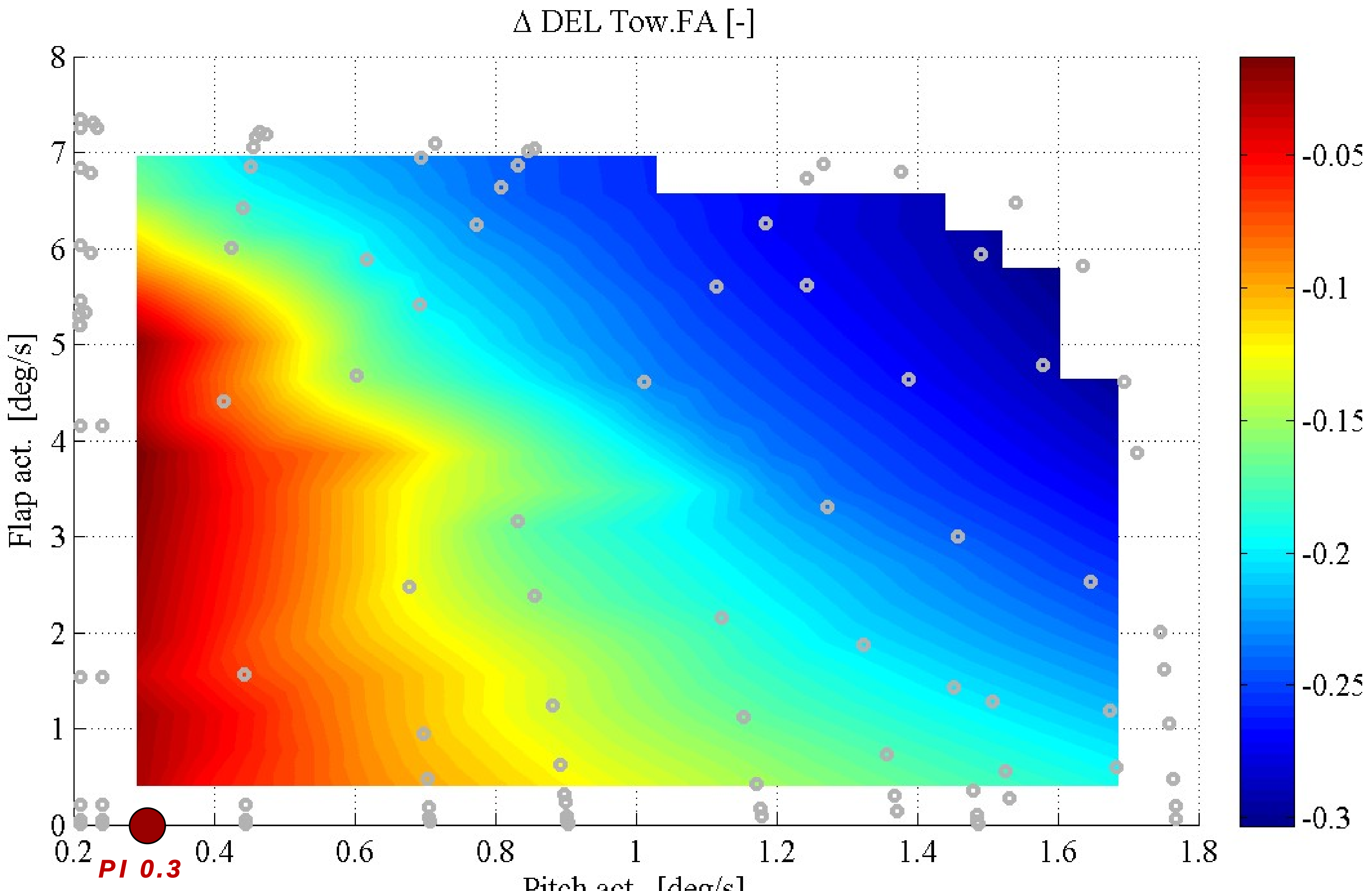
Application and results

Blade Root Loads: “cost-benefit”



Application and results

Effects on tower



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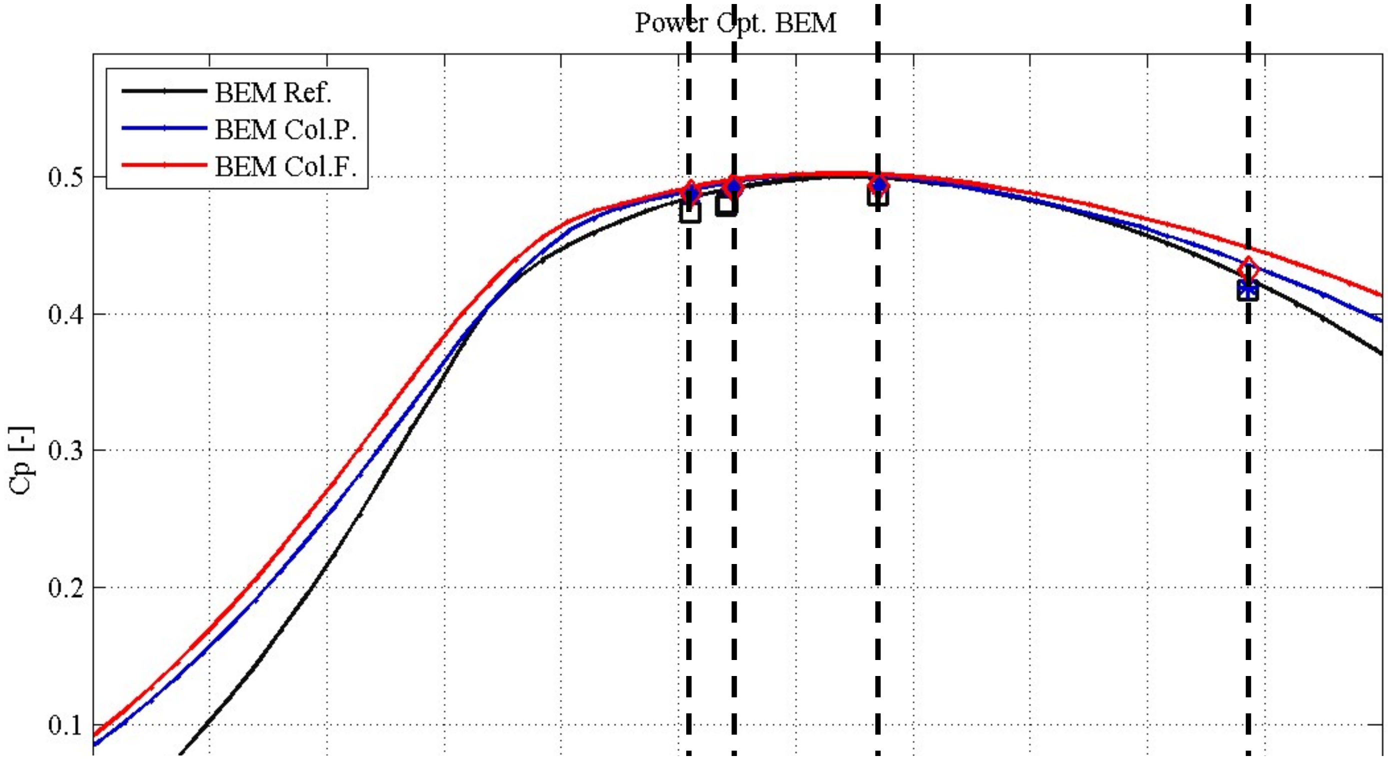
Increase power capture below rated

- Below rated: load alleviation not convenient
- Use Adaptive Trailing Edge Flaps to increase power capture?
- Simple BEM analysis (ideal rigid rotor):



- No gain at optimal Cp-Lambda

Quick-check with std. controller:

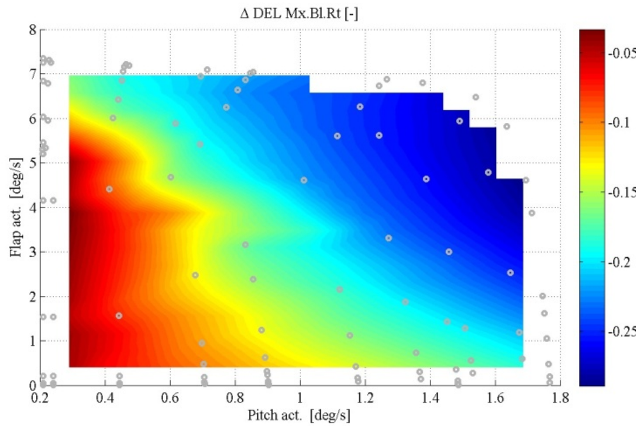
- Sub-optimal operational pts
- Tower frq.
- Variations around an operational point

IEC class II:

		Ref.	Col.P.	Col.F.	CPC	CPF
AEP	[GWh]	19.77	19.98	20.00	20.01	20.03
Δ AEP	[pct]	–	+1.08	+1.15	+1.24	+1.34

Conclusion

- “In union there is strength” applies to Smart Rotors
- MPC framework:
  - → Positive collaboration of pitch and flap actuators
- Advantages of combined actions: load alleviation
  - Increase alleviation potential: [15 %; 18 %] ➔ 30%
  - Spare pitch, take over with flap (or viceversa): 16 % + fl → 1/3
  - Alleviation on other parts of the structure
- Possibly enable other applications (future work)
  - Distributed actuators and sensors
  - Enhance power capture
  - Reducing loads in DT and speed variation
  - ...



Thank you…

A Model Based Control methodology combining Blade Pitch and Adaptive Trailing Edge Flaps in a common framework

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Leonardo Bergami, DTU Wind Energy
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Aeroelastics: next level challenges and solutions

**EWEA Wind Energy Conference,
Vienna, 4-7 February 2013**

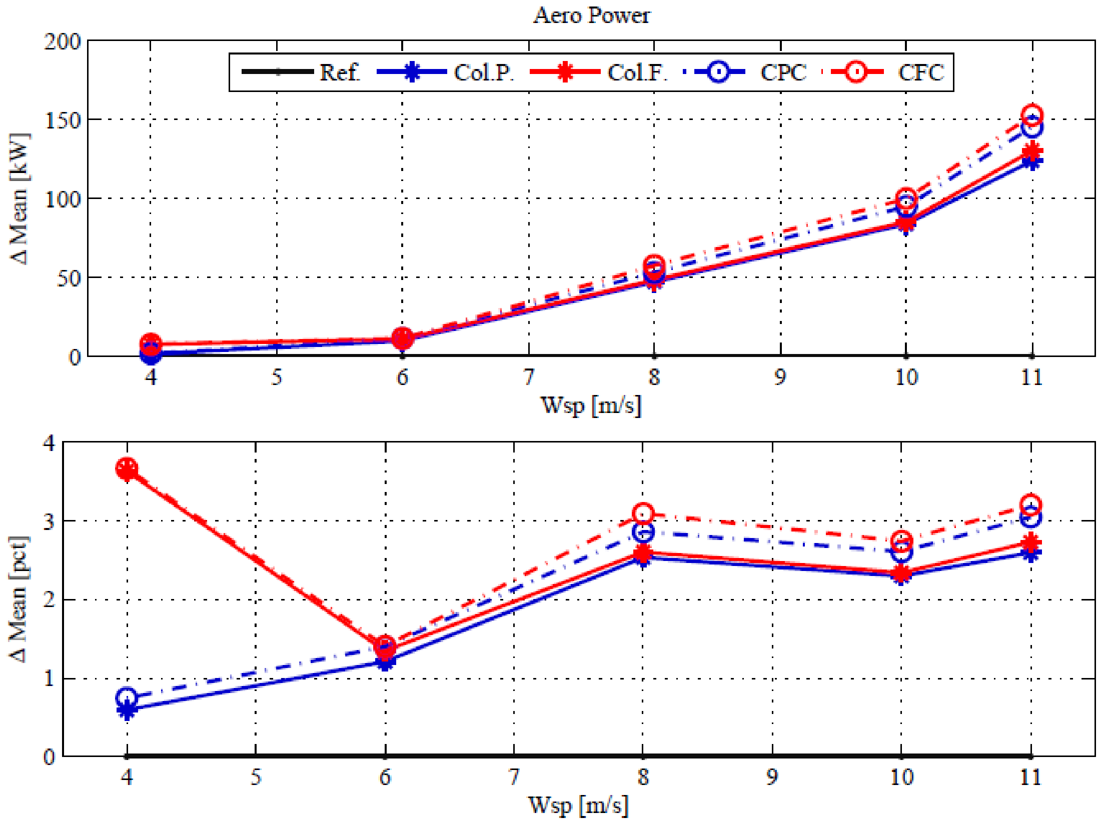
Bonus slides...

Other Applications: Increase power capture (concept)

Increase power: cyclic

- Simplified analysis: optimize power from cyclic flow variations
- Stiff rotor in deterministic (no turbulence) wind field

Results need to be confirmed in “realistic” conditions!



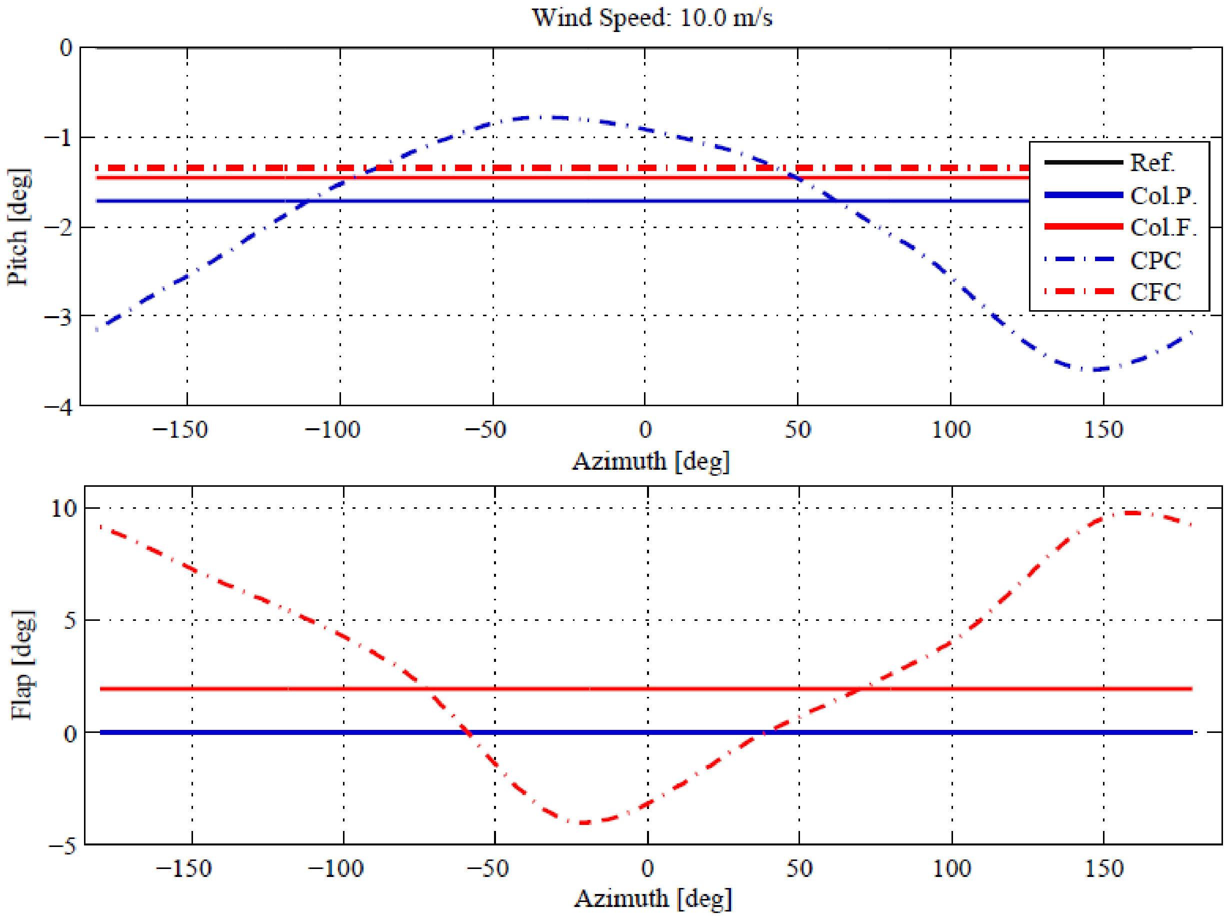
Cyclic trajectories for power increase load variation

IEC class II:

		Ref.	Col.P.	Col.F.	CPC	CPF
AEP	[GWh]	19.77	19.98	20.00	20.01	20.03
Δ AEP	[pct]	–	+1.08	+1.15	+1.24	+1.34

Increase power capture: cyclic trajectories

- Cyclic control action for increased power capture increases blade load variation



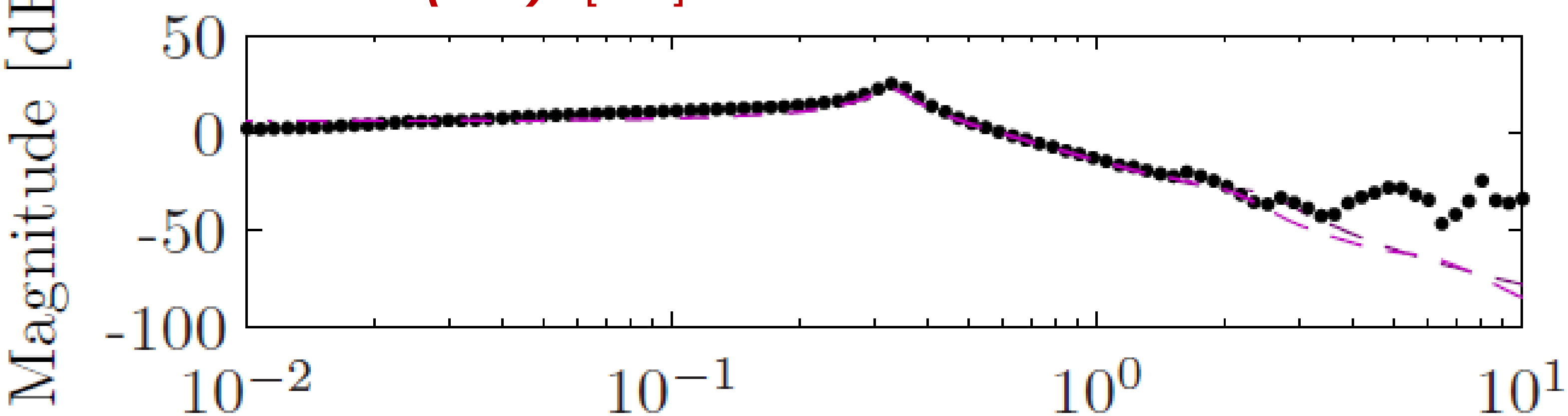
- As lambda increases, better Cp is in the direction of lower Ct

→ Amplifies load variation

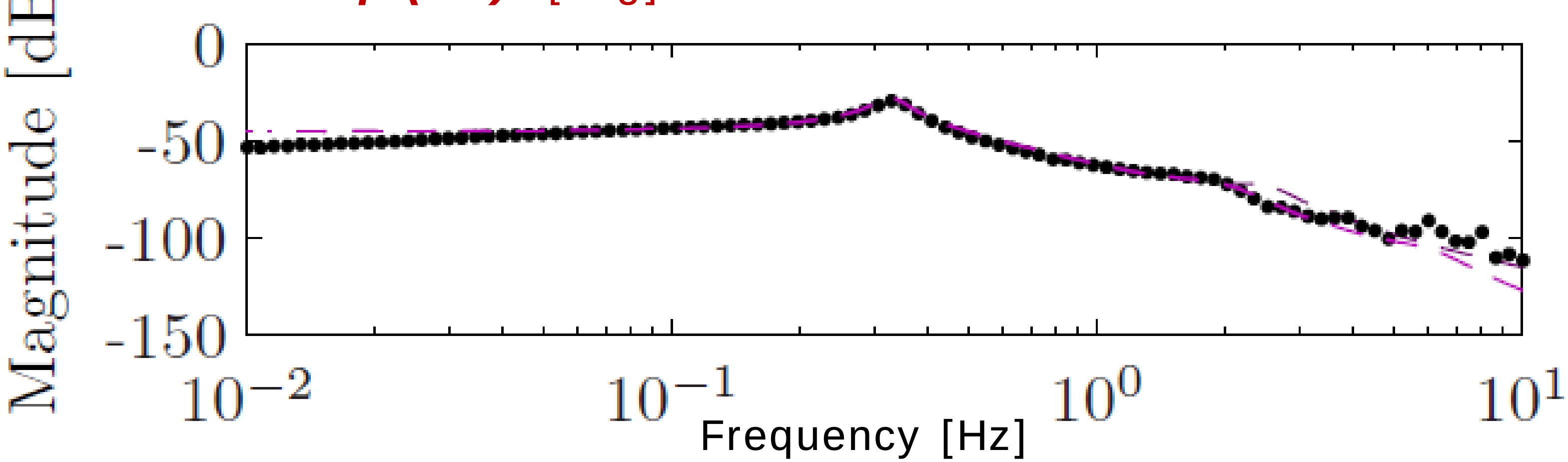
Verification: Response on tower bottom

Purple: 2+2 blade modes
Blue: 3+3 blade modes

- ***Pitch (th0):*** [rad]

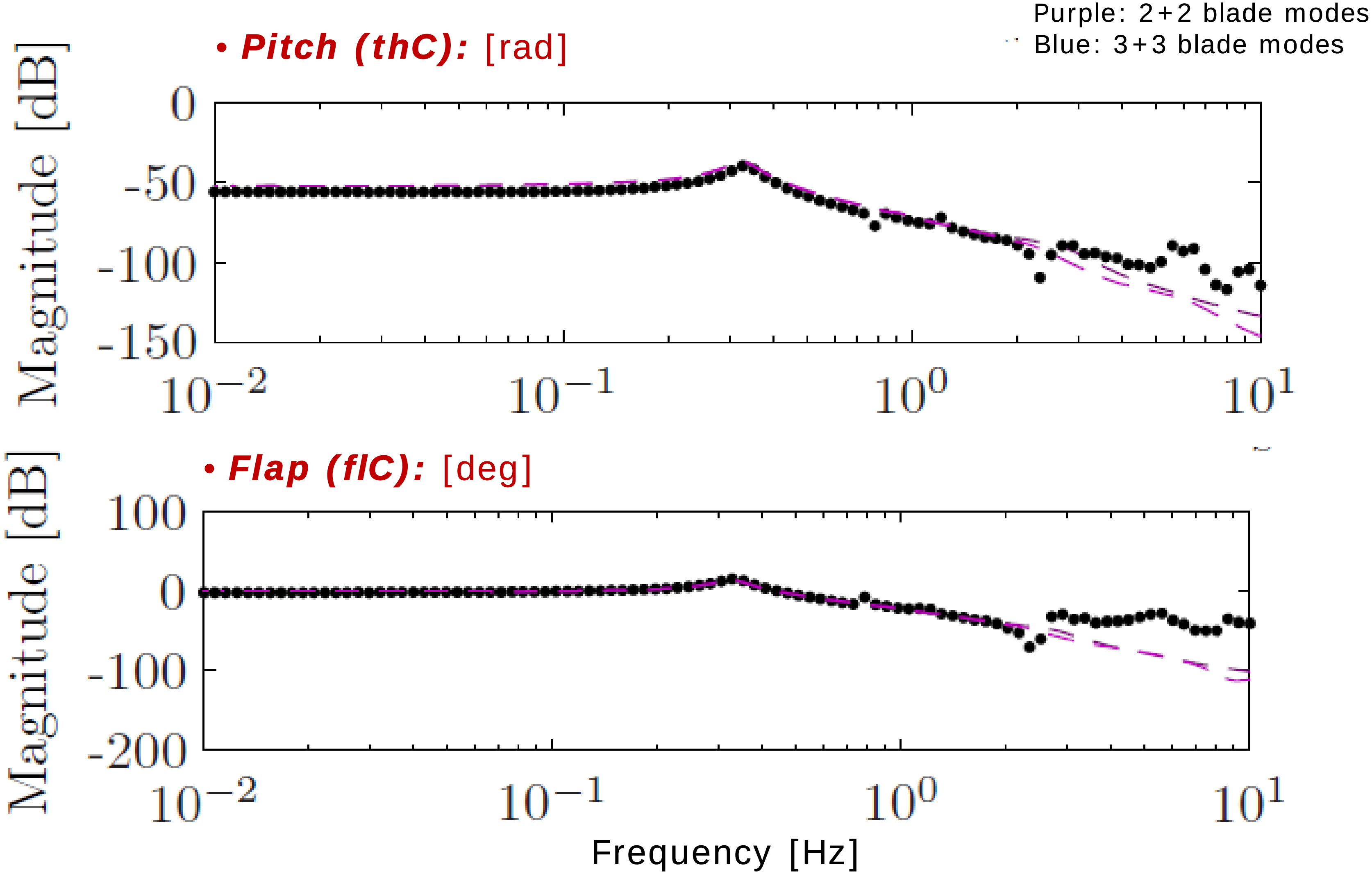


- ***Flap (fl0):*** [deg]



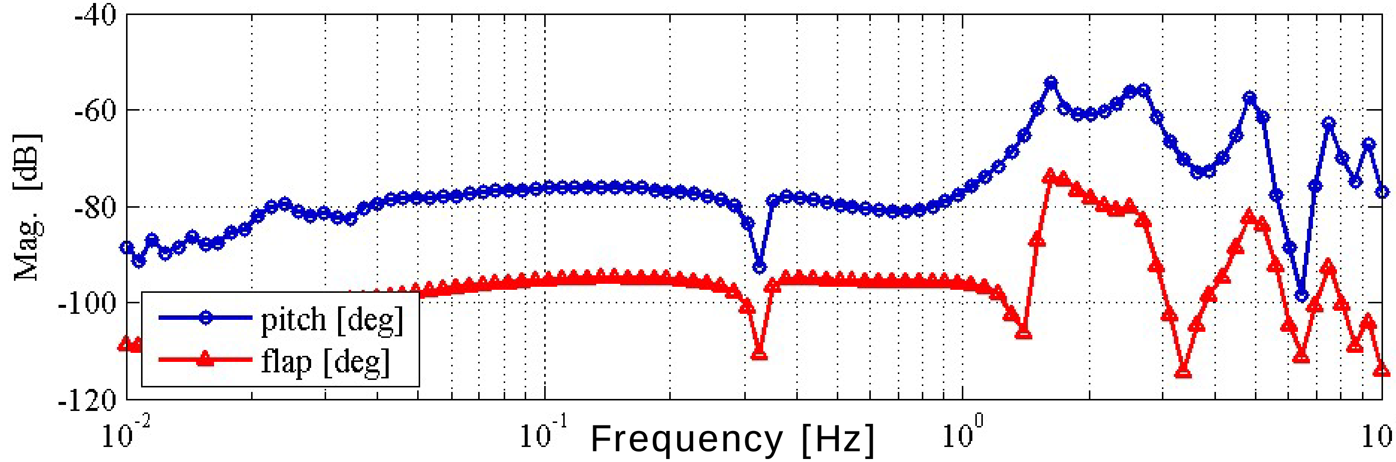
Verification: Response on tower bottom

- ***Pitch (thC):*** [rad]
- ***Flap (flC):*** [deg]



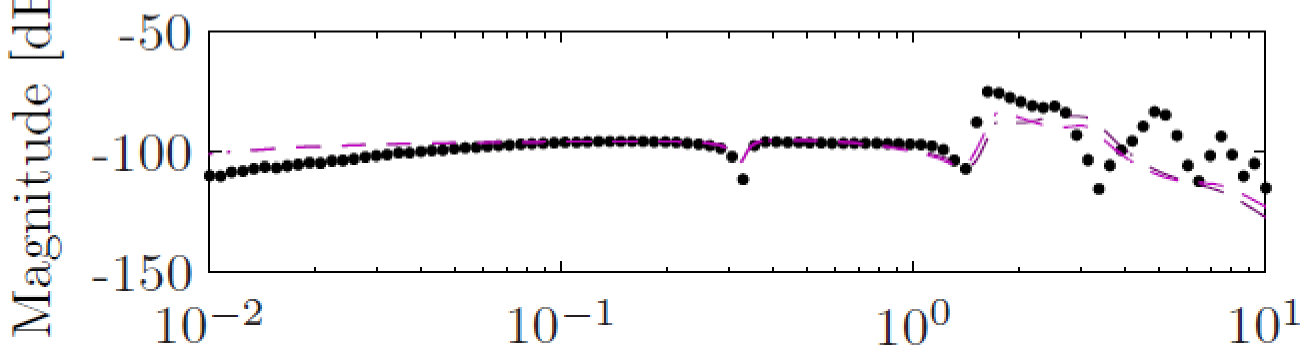
Drive train load alleviation (preliminary)

- Collective flap and pitch both have an effect on aero torque and shaft torsion



- Also modeled in the MPC framework:

Flap (fl0): [deg]



- Use flap to help in reduction of torque fluctuations → reduce DT requirements